Persistent altermagnets, nonlinear Edelstein effect and piezomagnetism

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Functional Quantum Matter Group
Max Planck Institute for the Physics of Complex Systems

mpipks

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Elastically Driven Phases and Dynamics in Quantum Materials
Ingelheim, Germany

http://www.pks.mpg.de/de/fqm

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Libor Šmejkal

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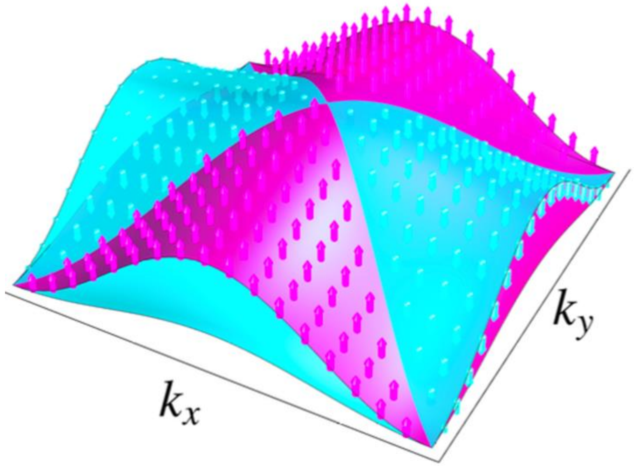
Outline

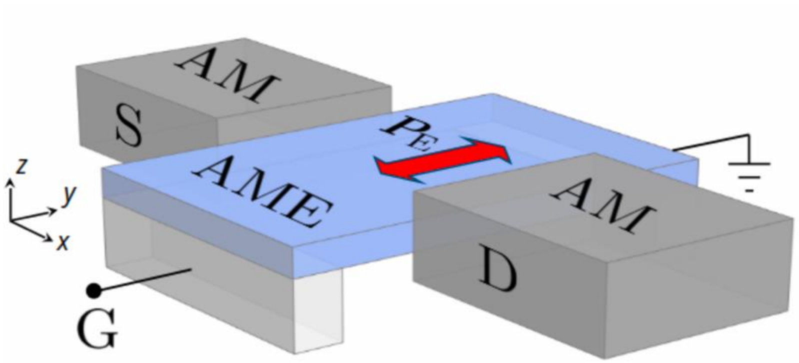
- Spin group classification of magnets
- Persistent altermagnetic spin polarization (PASP)

  Strong and weak persistent altermagnets

  Experimental observation
- Altermagnetoelectric effect with PASP

  PASP-enabled altermagnetoelectric spin filtering junction
- Nonlinear Edelstein effect in d-wave altermagnets
- Piezomagnetic-related effects in altermagnets





arXiv:2603.12223

W.H. Campos, F.C.F. Mbognou, A.B. Hellenes, J. Poata, T. Chen, J. Priessnitz, L. Šmejkal, arXiv:2603.12223.

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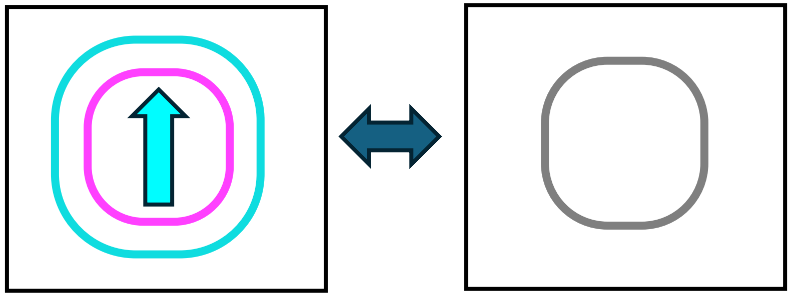
Spin group classification of magnets

Ferromagnets **Antiferro**magnets

Conventional



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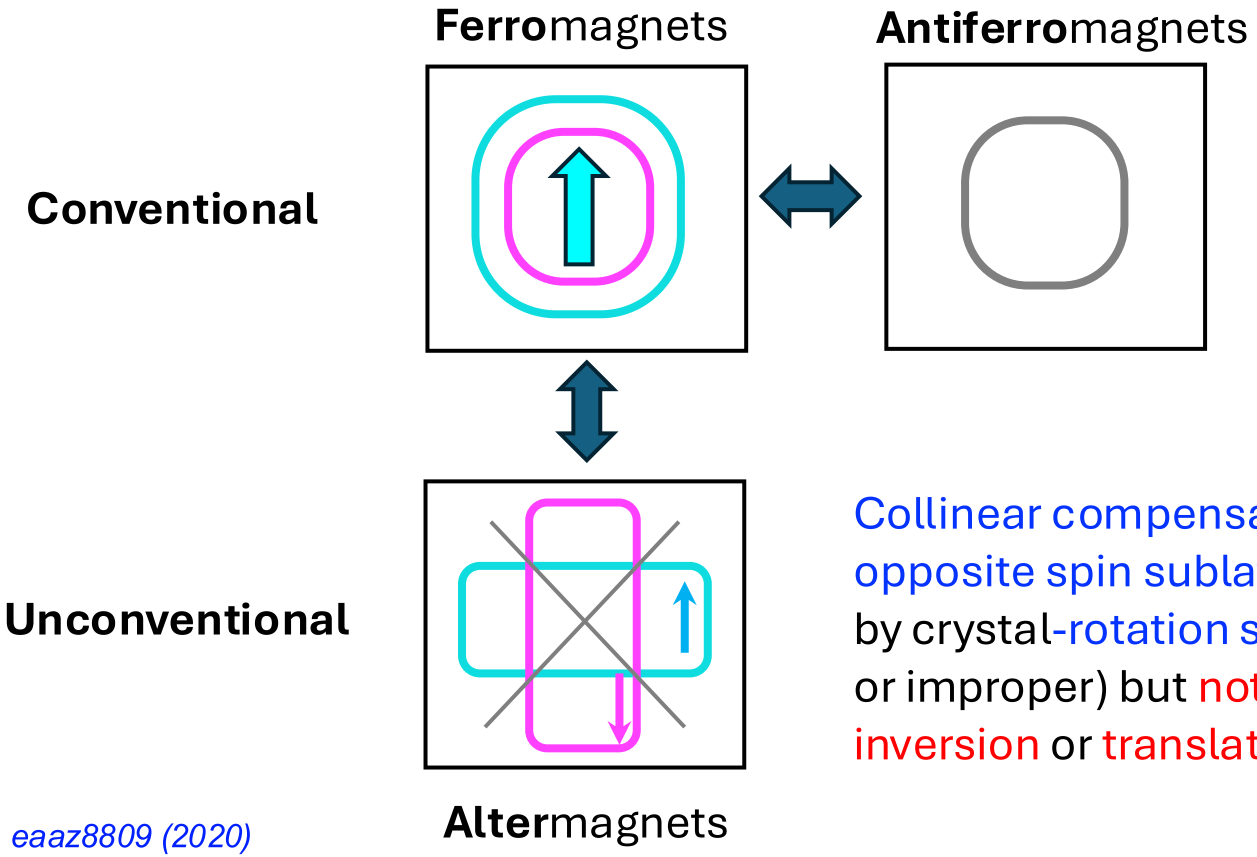
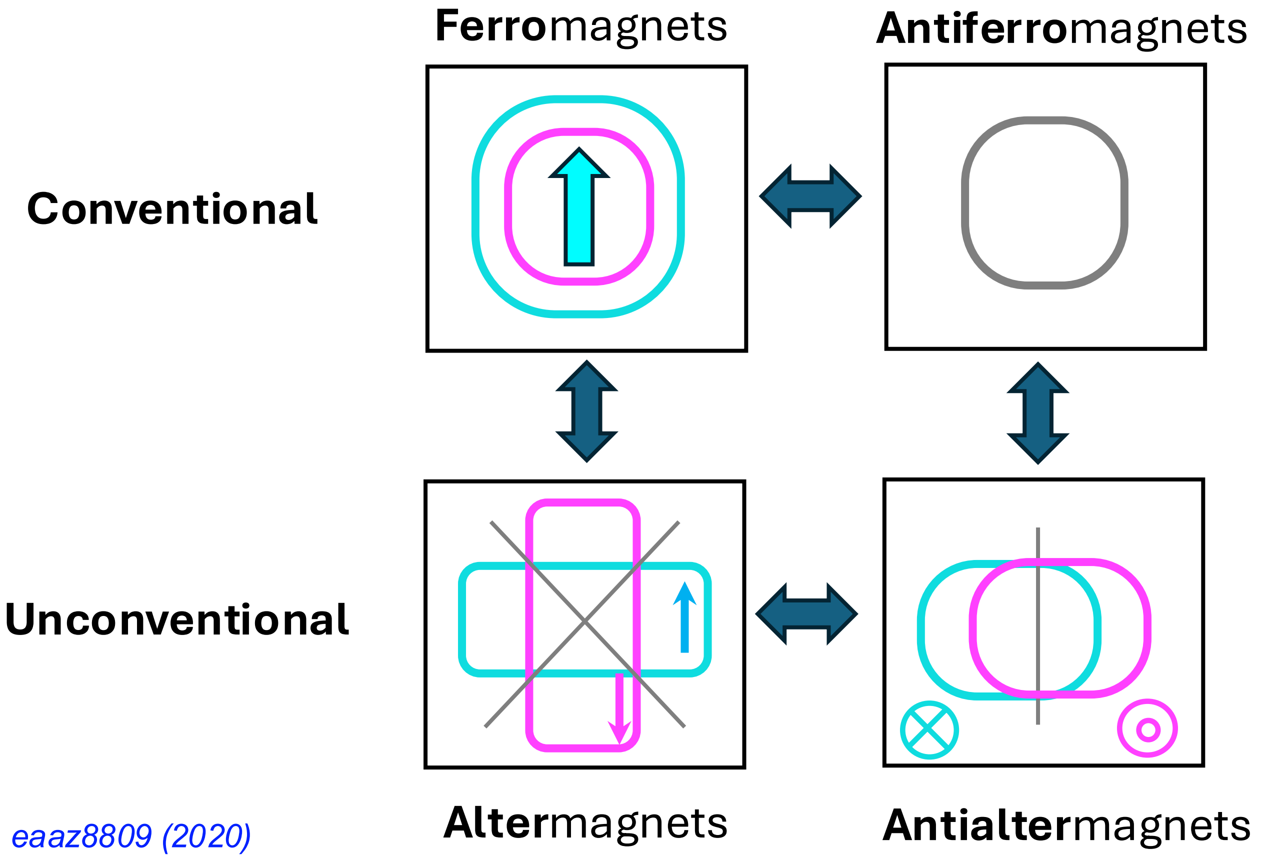
Spin group classification of magnets



Collinear compensated magnets with opposite spin sublattices connected by crystal-rotation symmetries (proper or improper) but not by crystal inversion or translation.

L. Šmejkal et al., Sci Adv. 6, eaaz8809 (2020)
L. Šmejkal et al., Phys. Rev. X 12, 031042 (2022); Phys. Rev. X 12, 040501 (2022)
H. Reichlova,…, L. Šmejkal et al., Nat. Comm. 15, 4961(2024)
Krempasky, L. Šmejkal et al., Nature 626, 517 (2024)
S. Reimers, L. Šmejkal, …, W.H. Campos et al., Nat. Commun. 15, 2116 (2024)
S. Lee, L. Šmejkal et al., Phys. Rev. Lett. 132, 036702 (2024)
A. Badura, W.H. Campos, L. Šmejkal et al., Nat. Commun. 16, 7111 (2025)
Šmejkal et al. Phys. Rev. Lett. 131, 256703 (2023)
Liu et al., Phys. Rev. Lett. 133, 156702 (2024)
Review: Jungwirth, Sinova, Fernandes, Liu, Watanabe, Murakami, Nakatsuji, and Šmejkal, Nature 649, 837 (2026)

Spin group classification of magnets



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A. Chakraborty,…, L. Šmejkal et al., Nature Comm. 16, 7270 (2025)
M. Khodas, L. Šmejkal, and I. Mazin, Phys. Rev. B 114, L080505 (2026)
J. Mitscherling,…, L. Šmejkal et al., arXiv:2603.09736

Spin group classification of magnets

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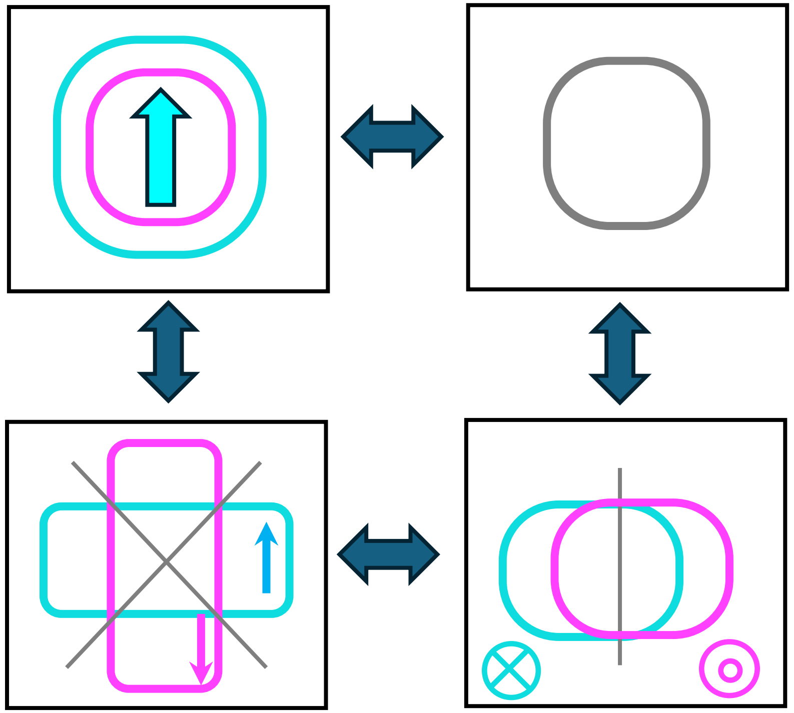
Conventional



Unconventional

Altermagnets **Antialter**magnets

L. Šmejkal et al., Sci Adv. 6, eaaz8809 (2020)
L. Šmejkal et al., Phys. Rev. X 12, 031042 (2022); Phys. Rev. X 12, 040501 (2022)
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J. Mitscherling,…, L. Šmejkal et al., arXiv:2603.09736

+ multiferroic variants

L. Šmejkal, arXiv:2411.19928

J. Priessnitz,…, L. Šmejkal et al., arXiv:2603.19107

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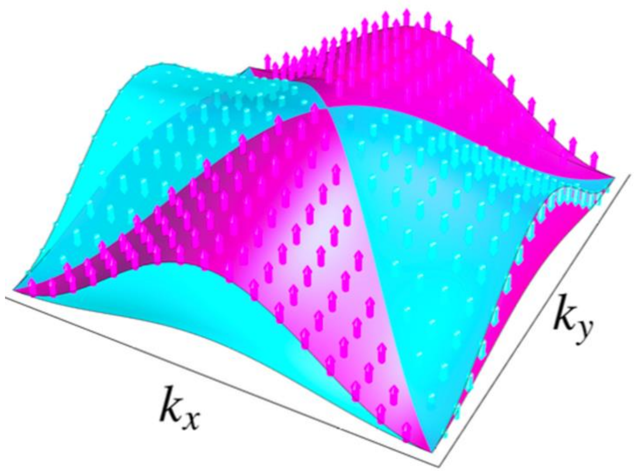

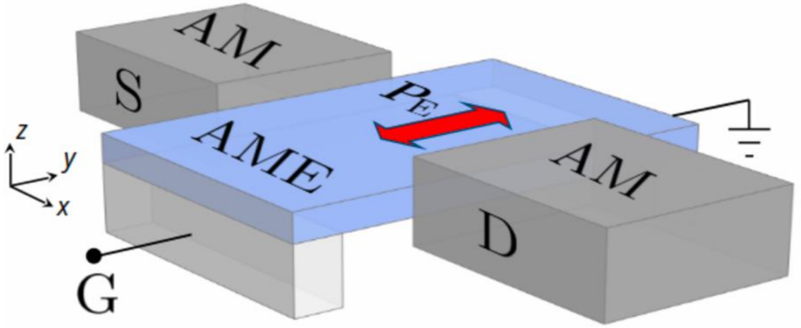

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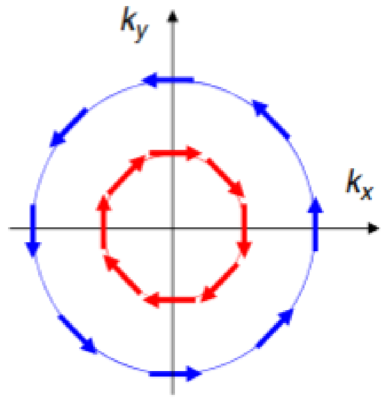
Motivation: Relativistic spin polarization

Spin-orbit coupling: $H_{\mathrm{SO}} = \boldsymbol{\Omega}(\boldsymbol{k}) \cdot \boldsymbol{\sigma}$

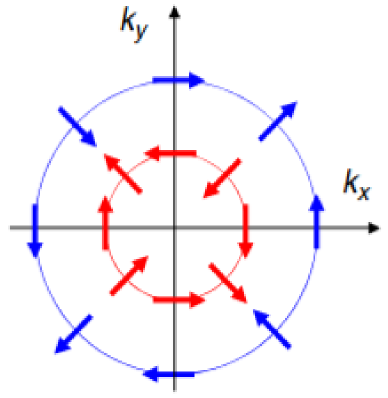
Rashba

$\boldsymbol{\Omega}_{\mathrm{R}} = \lambda_{\mathrm{R}}(-k_y, k_x, 0)$



Dresselhaus

$\boldsymbol{\Omega}_{\mathrm{D}} = \lambda_{\mathrm{D}}(k_y, k_x, 0)$



k-dependent spin polarization axis

L.L. Tao, E.Y. Tsymbal, Nat. Commun. **9**, 2763 (2018).
K. Zollner et al., Nat. Rev. Phys. 7, 1 (2025).

Spintronics applications

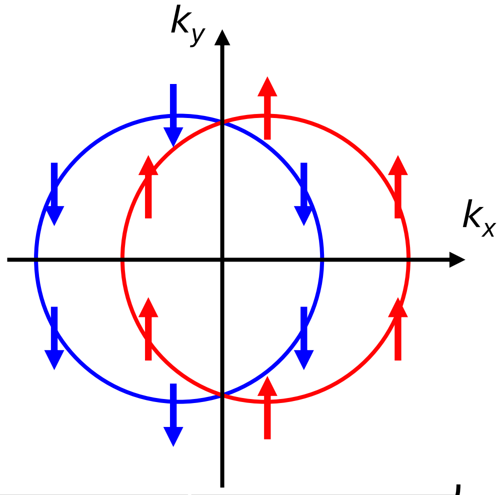
Spin relaxation $\longrightarrow$ $\boxed{\text{reduced spin lifetime}}$

k-independent spin polarization axis in the presence of SOC?

Rashba-Dresselhaus quantum well

$$\boldsymbol{\Omega}_{\mathrm{D}}(\boldsymbol{k}) + \boldsymbol{\Omega}_{\mathrm{R}}(\boldsymbol{k}) \xrightarrow{\lambda_{\mathrm{R}}=\lambda_{\mathrm{D}}=\lambda/2} \boldsymbol{\Omega}_{\mathrm{PST}}(\boldsymbol{k}) = \lambda(0, k_x, 0)$$

Schliemann *et al.*, PRL **90**,(2003)
Bernevig *et al.*, PRL **97** (2006)
Korlek *et al.*, Nature **458** (2009)



persistent spin texture

Collinear spin polarization $\longrightarrow$ long spin lifetime

Experimentally demanding

- Quantum well engineering, doping concentration, electric field
- Complicates fabrication and limits device integration

Weak spin splitting $\sim$0.01–0.1 eV

- Limits spintronic applications

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Can we circumvent these limitations with altermagnets?

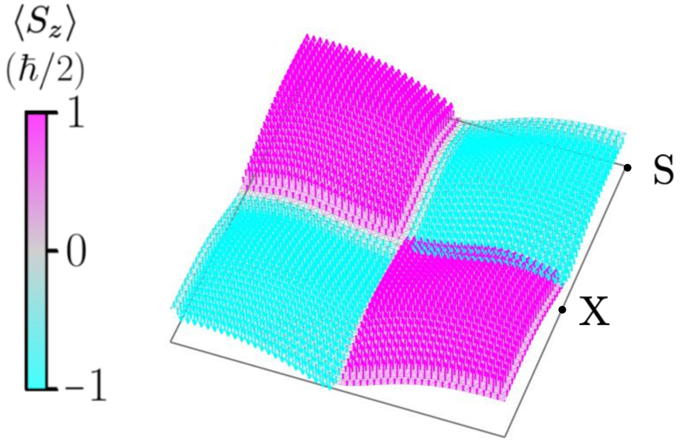
Typical scenario in altermagnets

Nonrelativistic
collinear spin polarization

Strong AM splitting from exchange origin

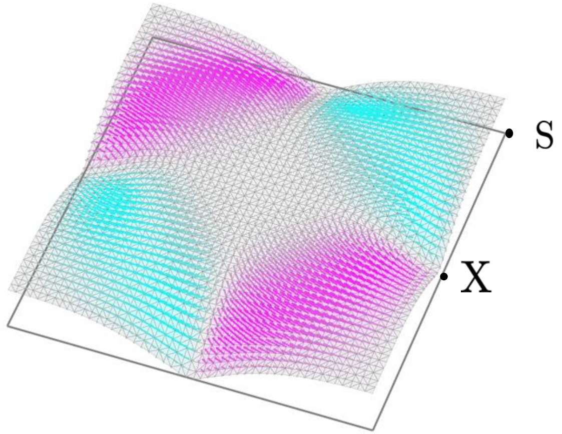
$\sim$ 1 eV

Experimentally feasible



SOC $\longrightarrow$

Relativistic
noncollinear spin polarization



Collinear spin polarization in AMs with SOC?

AM splitting in **2D** + **mirror symmetry**

$$M_z \boldsymbol{k} = \boldsymbol{k}$$

$$M_z S_{x(y)} = -S_{x(y)}$$

$$M_z S_z = S_z$$

arXiv:2603.12223

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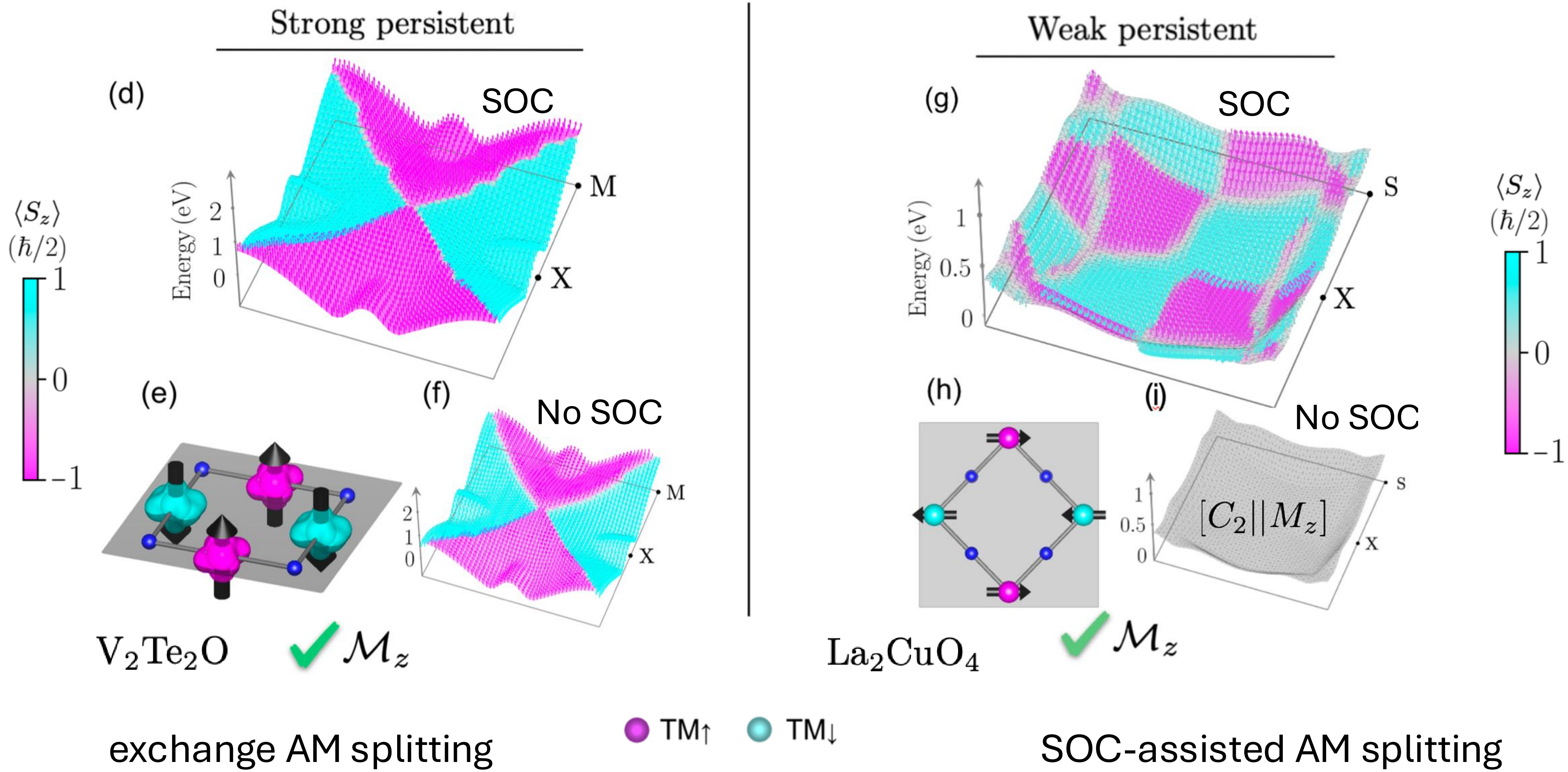
Persistent altermagnetic spin polarization (PASP)



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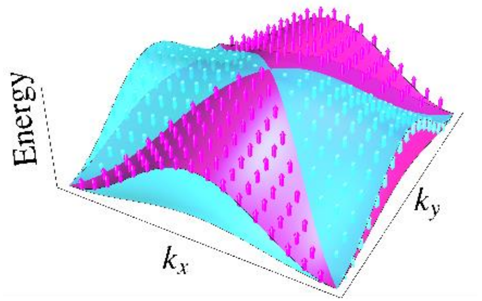
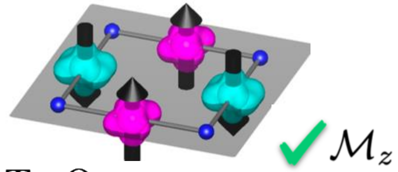
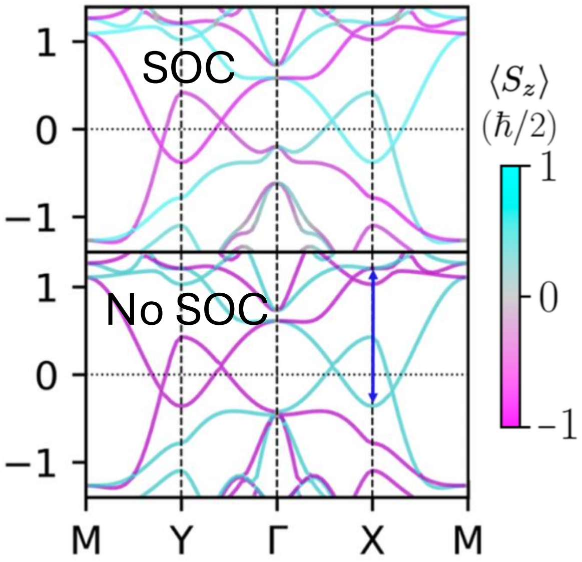




V_2Te_2O



Strong AM splitting from exchange origin

~1.5 eV

Robust spin collinearity

Mirror symmetry

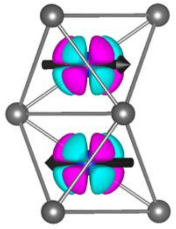
Experimentally feasible

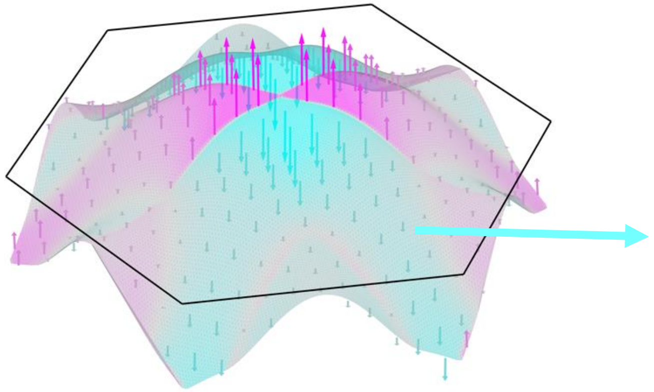
No quantum well engineering
Van der Waals layered compounds

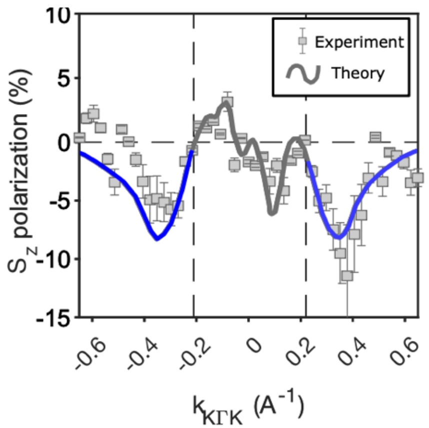
Multiple tuning possibilities

Néel vector
Magnetoelectric coupling
Strain
…

spin-resolved ARPES in MnTe k_z=0 plane







Dal Din, Usanov, Šmejkal, WHC & Wadley et al., arXiv:2511.01690

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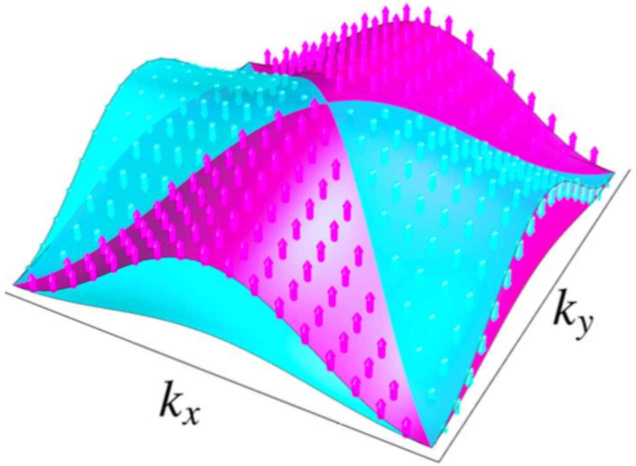

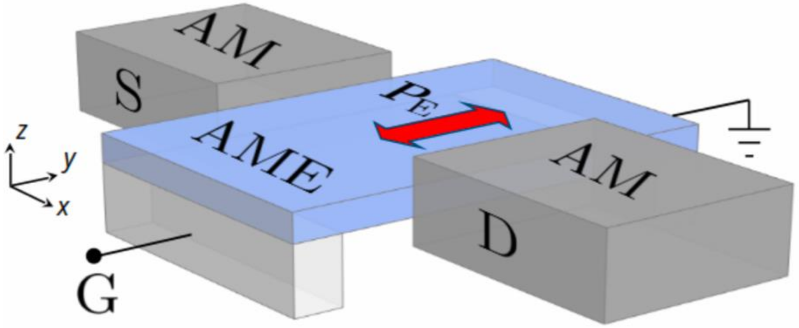

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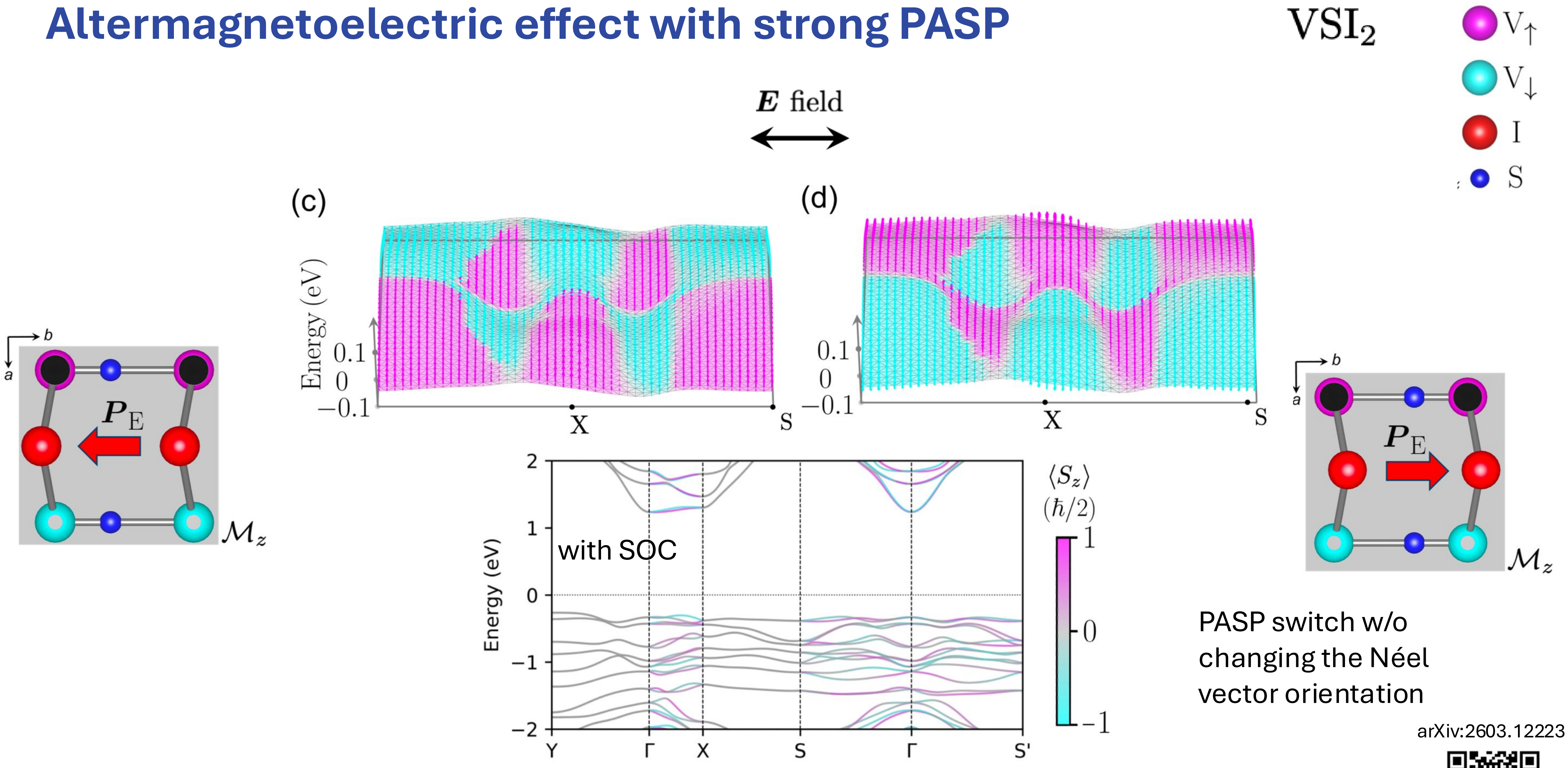
Altermagnetoelectric effect with strong PASP

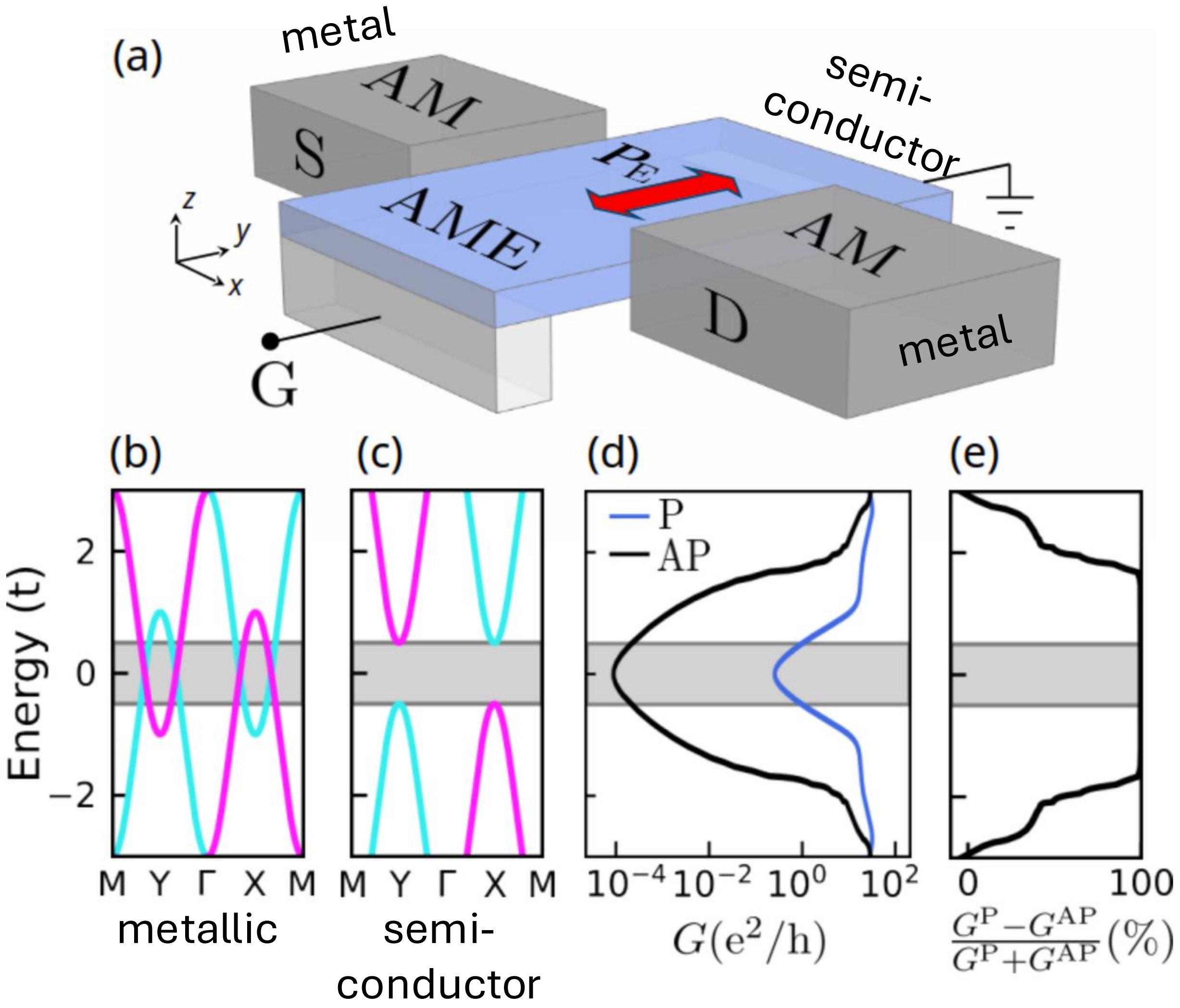


PASP switch w/o changing the Néel vector orientation

arXiv:2603.12223

L. Šmejkal, arXiv:2411.19928
W.H. Campos, F.C.F. Mbognou, A.B. Hellenes, J. Poata, T. Chen, J. Priessnitz, L. Šmejkal, arXiv:2603.12223.

PASP-enabled spin filtering junction



- Strong conductance suppression via electric gating
- Tunnelling magnetoresistance ratio ~ 100 %

Spin filtering junction

Magnetic state
- **Written** via AME effect
- **Read out** via tunneling magnetoresistance

Functionalities:
- **All-altermagnetic memory**
- **Spin-FET transistor**

arXiv:2603.12223

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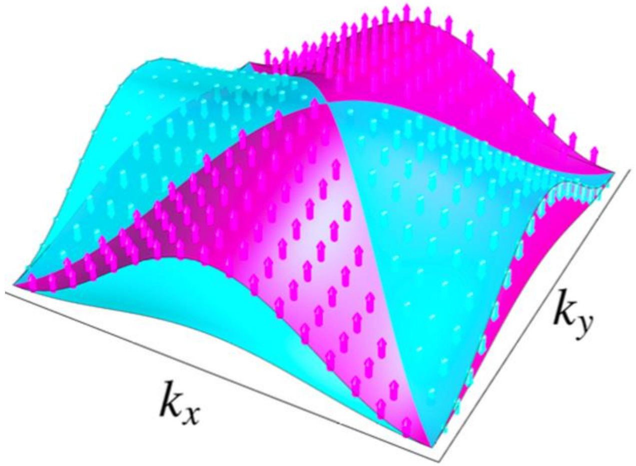

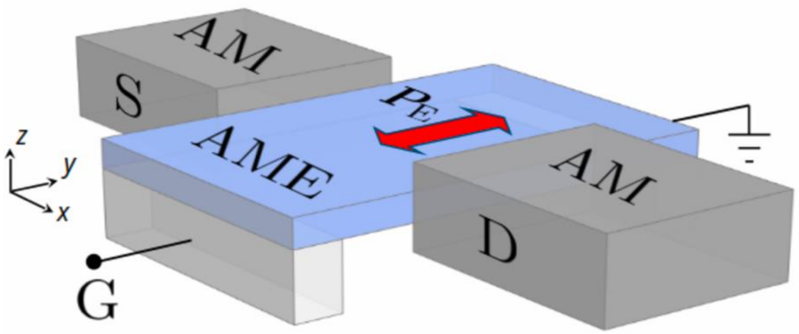

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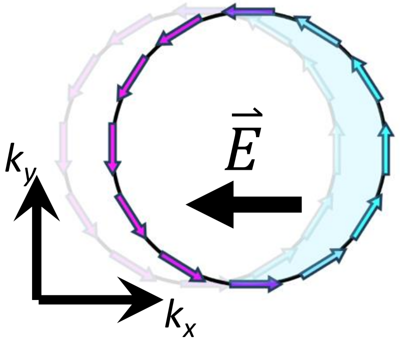
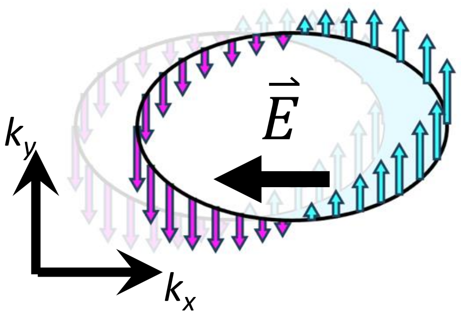
Nonlinear Edelstein effect

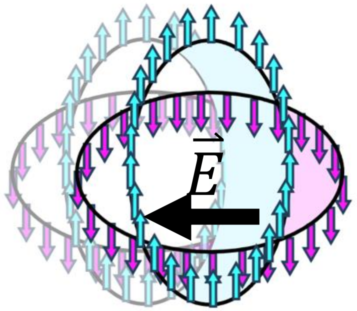
Edelstein effect

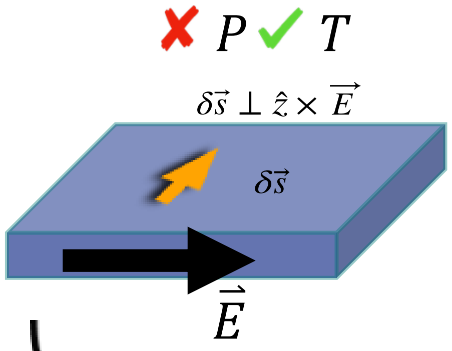


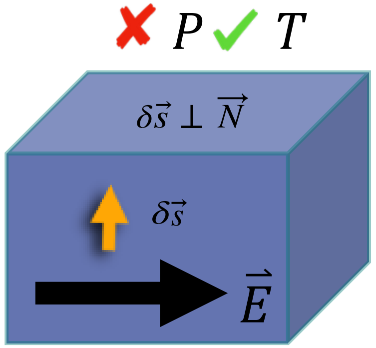
p-wave

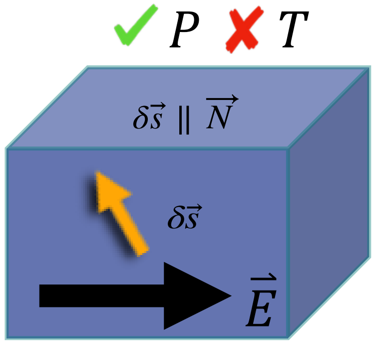


d-wave altermagnet







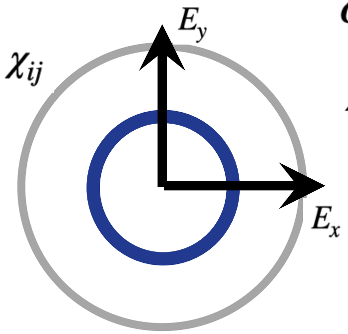


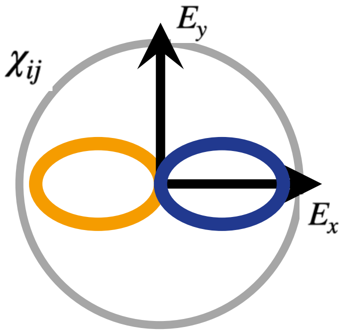
$$\delta s_i = \chi_{ijk} E_j E_k$$

$$\chi_{ijk} \propto \beta m \tau^2$$

$$\delta s_i = \chi_{ij} E_j$$

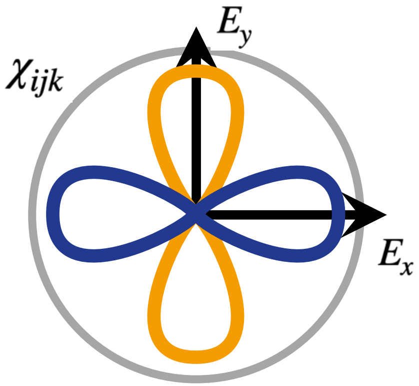
$$\chi_{ij} \propto \alpha m \tau$$





χ_{ijk} 2nd-order Spin susceptibility tensor

$M[V^2]$ Jahn symbol [Piezomagnetic]



Inherited d-wave symmetry detectable via MOKE

Class	SLG	$\chi_{ijl} \neq 0$	Materials
P-2	${}^2m^2m^1m$	$\chi_{xxy} = \chi_{xyx}$	Mn_5Si_3 [S11] CrSb $(u_{xx-yy})^*$ [S12]
	${}^24/{}^1m$	$\chi_{xxx} = -\chi_{xyy}$ $\chi_{xxy} = \chi_{xyx}$	$KRuO_4$ [S3]
	${}^24/{}^1m^2m^1m$	$\chi_{xxx} = -\chi_{xyy}$	V_2Te_2O [S13] $CaFe_4Al_8$ [S14] UCr_2Si_2C [S15]
B-2	${}^22/{}^2m$	$\chi_{xyz} = \chi_{xzy}$ $\chi_{xxz} = \chi_{xzx}$	$BiFeO_3$ [S16] CrSb $(u_{xy}/u_{zx})^*$ [S12]

V.M. Edelstein, Solid State Commun. ***73**, 233-235 (1990).*
A. Chakraborty, A.B. Hellenes, R. Jaeschke-Ubiergo, L. Šmejkal *et al.*, Nat. Commun. **16**, 7270 (2025)
N.A. Alvarez Pari, R. Jaeschke-Ubiergo, A. Chakraborty, L. Šmejkal, J. Sinova, Phys. Rev. B **112**, 024404 (2025)
L.E. Golub, **W.H. Campos**, **L. Šmejkal**, et al., arXiv:2503.12203

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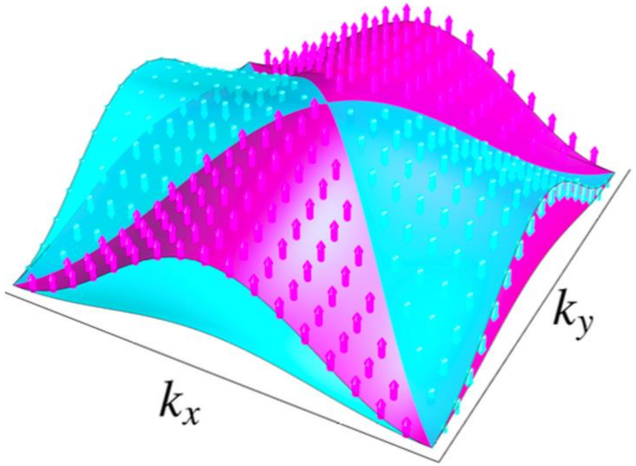

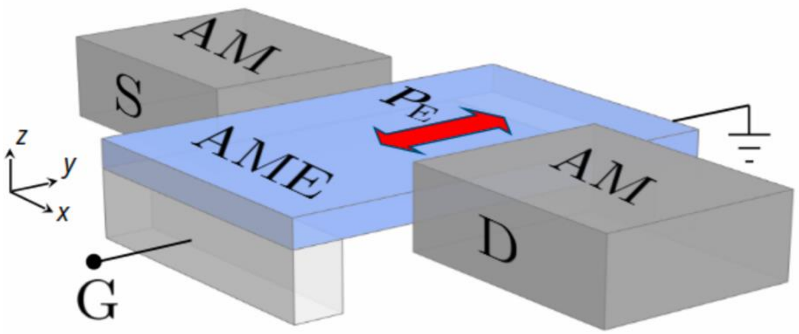

arXiv:2603.12223

W.H. Campos, F.C.F. Mbognou, A.B. Hellenes, J. Poata, T. Chen, J. Priessnitz, L. Šmejkal, arXiv:2603.12223.

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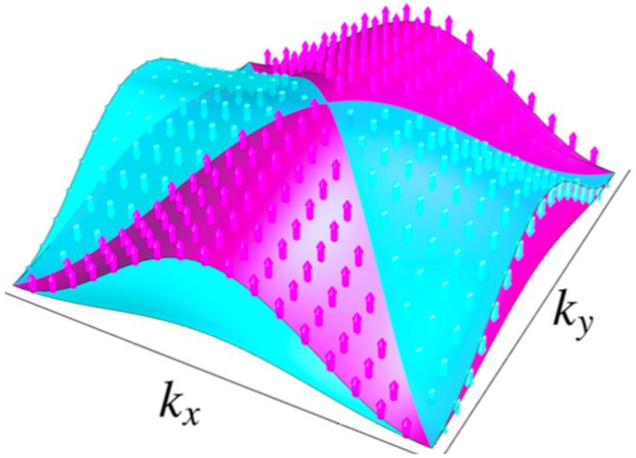
Summary

Altermagnets: New class of collinear compensated magnets with broken TRS



Persistent altermagnetic spin polarization (PASP)

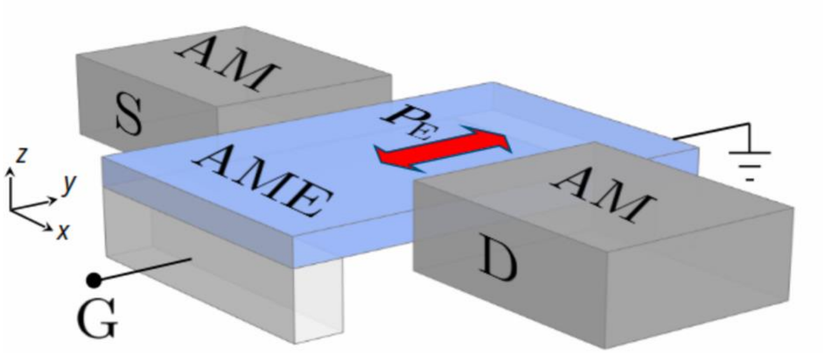
Protected by **mirror symmetry**

Strong: exchange-origin AM splitting
Weak: SOC-assisted AM splitting

Observation of weak PASP in MnTe

Functionality: All-altermagnetic memory or spin-FET transistor

Electrical control w/o Néel vector manipulation



Nonlinear Edelstein effect: Piezomagnetic response in d-wave metallic altermagnets

Piezomangetic-related effects in altermagnets

Thank you for your attention!

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